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PASSIVELY MODE-LOCKED 2 MICRON LASER

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NOTICE

This technical report has been reviewed and is approved for publication.

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A mode-locked, room temperature, 2-micron laser system was demonstrated with 1% wall plug efficiency. It produced 100 mW average power at 2.063 microns with 10 watts of electrical power to the diode pump. The viability of solid state mode locking at 2 microns was demonstrated. This technology will be continued under the auspices of an AFOSR initiative, workunit 2301EL01.

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1. INTRODUCTION

This technical report summarizes the in-house Innovative Laboratory Independent Research (ILIR) accomplishments of Electro-Optics Sources (WL/ELOS) personnel under workunit 0100EL24. The objective of this workunit was to develop and demonstrate an all solid-state, 2-μm, passively mode-locked laser. For further detail on the technical accomplishments of this workunit, the papers referenced in the text below may be consulted.

A passively mode-locked architecture was pursued to decrease the size, weight and radio frequency electrical power requirements that are associated with an active mode-locking design. This approach was used to develop a highly reliable, low maintenance, and very efficient mid-IR laser source. The basic laser was to be mode-locked with an output wavelength near 2 μm. The mode-locked pulse train was to possess sufficient peak power to produce efficient parametric frequency conversion throughout the 2-5 μm band. This could be accomplished by synchronously pumping an optical parametric oscillator with 2-μm mode-locked pulses. However, this program concentrated on the development of a laser source and left the OPO work for the future.

The inspiration for using solid-state passive mode-locking came from a paper published in *Applied Physics Letters* in 1991. Vodopyanov *et al.* were able to mode-lock a laser operating at 3 μm.[1] A 270-nm layer of InAs was epitaxially grown on a 250-μm thick GaAs wafer to produce a fast acting, periodic loss

modulation inside the laser cavity. The losses inside the wafer were modulated by a fast saturation of a transition to the conduction band in the InAs epilayer. The pulse duration was determined to be in the range of 20-30 psec. In 1992, Zhang *et al.* reported use of just a 500-μm insulating wafer of GaAs to produce 10-psec pulses from a Nd:YAG laser.[2] This report added reassurance that the primary ingredient is a saturable absorber with a fast recovery time and a low saturation level. Also in 1992, Keller *et al.* described a new configuration for mode-locking Nd:YLF and Nd:YAG lasers.[3] This design used a multiple quantum well (MQW) superlattice with layer composition that was nearly matched to the photon energy of the lasers. Additionally, the MQW superlattice was placed within an intracavity antiresonant Fabry-Perot device which made the laser intensity on the saturable absorber lower preventing damage to the mode-locker.

We decided to investigate a very simple, single epilayer of $In_xGa_{1-x}As$ on a suitable substrate which could provide the proper loss modulation at 2 μm wavelength. The value of x was experimentally varied until material with a bandgap slightly greater than 2 μm was produced. Two substrates were chosen, GaAs and InP, due to their compatibility and close lattice matching to InGaAs. The saturable absorber development occurred simultaneously with the creation of the laser source and is discussed in the next section.

The preliminary research for this effort occurred during a collaboration via the Windows on Europe program in which Dr

Schepler spent three months in 1991 working at the Laser-Physik Institut, Universität Hamburg, Germany. During this time the viability of mode-locked 2-μm lasers was demonstrated. A Tm:YAG laser pumped by a krypton laser demonstrated mode locked pulse widths as short as 41 psec. [4,5,6]

The subsequent ILIR work was performed over a 2-year span by the following personnel:

Dr. Kenneth L. Schepler

Capt. Brian D. Smith

In addition, the following made valuable contributions:

Dr. Peter A. Budni	Lockheed Sanders, collaboration
Dr. Günter Huber	Universität Hamburg, collaboration
Dr. Ernst Heumann	Universität Hamburg, collaboration
Mr. Frank Heine	Universität Hamburg, Window on Science, collaboration, (PhD candidate)
Dr. Ronald Kaspi	NRC fellowship to WL/ELRA, collaboration
Dr. Wayne Pelouch	NRC fellowship to PL/LIDD, collaboration
Dr. Vern Schlie	PL/LIDD, collaboration
Mr. Edward Stutz	WL/ELRA, collaboration

2. TECHNICAL ACCOMPLISHMENTS

Efforts concentrating on the design, assembly and demonstration of a diode-pumped, 2-μm, mode-locked laser were at the core of the program. In order to quickly demonstrate mode-locking of 2-μm lasers, active intracavity mode-locking was demonstrated first. The 2-μm laser was run continuous wave (CW) and mode-locked at room temperature using a 6% Tm, 0.5% Ho:YLF laser rod pumped by a 3-W CW diode laser operating at 795 nm (Fig. 1). CW output yielded 220 mW through a 2% output coupler. Mode-locking was achieved using a NEOS $LiNbO_3$ acousto-optic mode-locker (AOML) driven at a resonant frequency of 150 MHz. The laser cavity was set to an effective round trip length of 100 cm. As expected, mode-locked pulses were formed with a repetition rate of 300 MHz. An autocorrelator borrowed from Universität Hamburg was successfully used to determine that the mode-locked pulses had an approximately gaussian profile with 370 psec pulse widths. The system operated stably at 100 mW of average power. The laser was also operated with the laser crystal inside a LN_2 dewar. The laser power was 380 mW CW and 300 mW mode-locked. [7,8]

A custom designed, 2-μm autocorrelator has since been built in our lab for future measurements of pulse width. The translating mirror has 15 cm of travel, which will allow the characterization of pulses from 8 fsec to 500 psec.

A G1.5 Molecular Beam Epitaxy (MBE) machine operated by WL/ELR was used to grow InGaAs epilayers for our saturable absorption testing. Five of the wafers used a GaAs substrate and

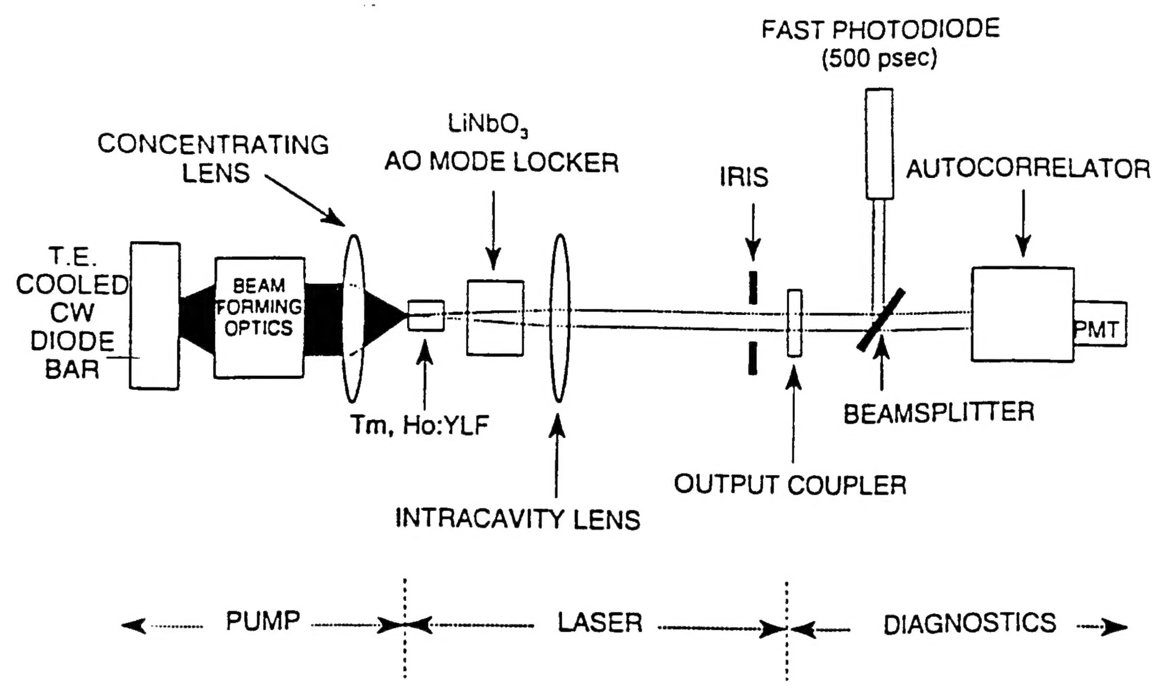

Figure 1. Setup for solid-state, 2-μm, mode-locked laser.

five used InP. The thickness of the epilayers ranged from 100 nm to 3 μm. The thicker samples were used to determine the bandgap of the epilayer based on their spectral transmission as measured by a spectrophotometer operating in the mid-IR.

Although no mode-locking was ever observed with these monolithic (as opposed to MQW devices), a pulsed Cr,Tm,Ho:YAG laser produced 40 nsec Q-switched pulses. [9] However, the wafers damaged after a few pulses indicating that damage was occurring at or below 10 MW/cm^2.

In order to better understand the saturable absorption mechanism and measure the recovery time we loaned samples to personnel at PL/LIDD. They studied the time dependent characteristics of saturable absorption using a sample with a 300-nm epilayer, $In_{.65}Ga_{.35}As/GaAs$ structure. The experimental configuration consisted of a synchronously pumped, mode-locked $Ti:Al_2O_3$ laser pumping a KTP optical parametric oscillator tuned from 1.5 to 1.8 μm. By using the technique of time correlated photoluminescence, a saturation with ultrafast relaxation from 200 to 400 fsec was measured at room temperature. [10] This type of relaxation occurs in all semiconducting materials due to a fast phonon scattering phenomenon encountered during high intensity optical pumping. Carrier recombination in the epilayer of our sample is a slower process and ranged from 2.5 to 10 psec at room temperature. Typical pumping conditions for the sample included a 1.8-μm beam wavelength, a 30-μm diameter spot, 85 fsec probe pulse duration, and 80 MHz pulse repetition frequency. The laser system generated a peak intensity of 4.2 GW/cm^2, yet

maintained a peak fluence of only 360 $\mu J/cm^2$. These conditions provided for efficient generation of nonlinear phenomena while reducing the risk of damaging optical components.

The PL/LIDD measurements indicated that fast phonon scattering was difficult to saturate preventing significant changes in absorption. This made our samples poor candidates for mode locking. However, as mentioned earlier in the report, there are other approaches using MQW configurations which may be more amenable to saturation at low powers and are resistant to damage. These will be investigated in a follow-on research program.

3. CONCLUSION

A mode-locked, room temperature, 2-μm laser system was demonstrated with 1% wall plug efficiency. It produced 100 mW average power at 2.063 μm with 10 watts of electrical power to the diode. The viability of solid-state modelocking at 2 μm was demonstrated. This technology will be continued under the auspices of an AFOSR-funded Infrared Countermeasures Initiative. Results will be documented under workunit 2301EL01.

Further research is required in the following areas: (1) reduction of the 2-μm mode-locked pulse widths, and (2) increasing the average power available for OPO output. Two approaches are being considered as ways to address pulse width reduction. The first approach is to use the MQW design described in the introduction. Absorption should be much easier to saturate in such a material with its low density of states near the band edge.

The second approach is to use a fiber laser developed by Raytheon as an injection seed to our bulk crystal Tm:YLF laser. The Raytheon laser is a diode pumped, passively mode-locked fiber laser which operates at 1.906 nm at its peak with several nanometers of linewidth. The mode-locker is an InGaAs/GaAs MQW design like the one designed originally at AT&T Bell Labs. The output pulse width can be as short as 200 fsec at 50 MHz with 1 mW of average power. This laser will seed our Tm:YLF laser which was shown to operate at 1.908 μm. Seeding should allow us to maintain short pulse widths while scaling up the average

output power two orders of magnitude to hopefully produce 100 mW of average power at room temperature.

Finally, co-doped Tm-Ho crystals have either not produced modelocking or the pulses have been longer than expected. Further investigations of the mechanism behind this are planned.

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